

Seismic monitoring and vibrational characterization of small wind turbines: A case study of the potential effects on the Eskdalemuir International Monitoring System Station in Scotland

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ABSTRACT

This paper presents a case study of the ground-borne vibrations generated by small wind turbines. This is of particular importance for assessing the possible impact on the detection capabilities of the International Monitoring System seismic array at Eskdalemuir in Scotland. Measurements were gathered from a selection of small wind turbines (≤ 50 kW), from three different manufacturers, varying in hub height, power and construction using a range of accelerometers and seismometers fixed to the tower and buried in the adjacent ground at increasing distances. Previous studies have shown that medium and large turbines generate harmonic vibrations. Planning guidelines exist but have inadvertently led to a ban on the deployment of individual small-turbines within 50 km of the array. This study investigates whether their inclusion in these guidelines is necessary.

Vibration levels on the tower are in the region of 10^{-3} m/sqrt(Hz), are transferred into the ground and decay rapidly away from the turbine (10^{-5} m/sqrt(Hz) in the ground at 200 m). The spectral content of the vibrations shows variations between the turbines, but each have peaks in the band of interest for Eskdalemuir. Further, sources of the peaks in the spectra are identified as either originating from the blades' rotation or the resonant modes of the turbines.

Analysis of the relationship between wind speed and seismic amplitude on the tower shows an exponential trend, individual to each wind turbine and the frequency band of interest. Similarly, analysis of the seismic amplitude between the tower and foundation shows that this can be described by a power law, but this is individual to each turbine. It is our opinion that there is little requirement to include turbines of 50 kW or less in planning guidelines outside the statutory exclusion zone of 10 km, but each turbine should be considered on an individual basis.

INTRODUCTION

Renewable energy sources, especially wind power, have become a focus of energy policies in many countries. The small wind market, that is wind turbines with a rated power of less than 50 kW, has seen particularly strong growth across the world with global capacity, according to the World Wind Energy Association, totalling more than 576 MW. This is expected to increase with a forecast of an additional 1000 MW of new capacity being installed annually by 2020, which would provide a cumulative total of 5 GW of installed worldwide capacity (Gsänger 2013).

By design, wind turbines have to be located at sites with high wind speeds. This leads to high forces acting upon the tower and the blades, causing vibrations throughout the structure. Some of these can be detrimental to the turbine, whilst others are trans-

ferred into the ground and can propagate to distances of 10 km or more (Styles *et al.* 2005).

Current literature specifically focusses on vibrations of the wind turbine blades (Liu 2013; Yang and Sun 2013; Skrzypiński and Gaunaa 2014; Zhou *et al.* 2014); the gearbox (Zhang *et al.* 2012); and the effect of earthquakes and seismic activity on the turbine (Díaz and Suárez 2013; Taddei and Meskouris 2014). Additionally, there is considerable research in the field of low frequency noise and infrasound from wind turbines (Jakobsen 2005; Pedersen and Waye 2008; Dijkstra and Kerckers 2011; Guarnaccia *et al.* 2011; Møller and Pedersen 2011; Taylor *et al.* 2013; de Beer 2013; Mollasalehi *et al.* 2013; Larsson and Öhlund 2014). However, there is limited work available which examines how low frequency vibrations from wind turbines affect the surrounding ground and nearby structures, and all focus on large wind turbines (Legerton *et al.* 1996; Schofield

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2002; Styles *et al.* 2005; Fiori *et al.* 2009; Saccorotti *et al.* 2011).

This paper looks at the results of monitoring the vibrations from four small wind turbines located at sites around the UK (Fig. 1) and varying in rated power, tower height and construction. A case study focussed on the Eskdalemuir seismological array (station code EKA) in Scotland is used to demonstrate whether the vibrations could affect the listening capabilities of the station, which is a component of the International Monitoring System (IMS) for the Comprehensive Nuclear-Test Ban Treaty (CTBT).

This work aims to characterise the spectral characteristics of small wind turbines, so that they could be included in operational planning requirements for wind farm development in the Scottish Southern Uplands. This would probably be operated in a generic manner and has already been adopted for larger wind turbines. The decisions on planning permission are from a huge range of site locations where the specific site geology is unlikely to be known, as that is not part of the planning procedure.

Following this introduction, the paper provides an overview of the EKA array, detailing why this site is a good case study to use. This is followed by an explanation of the data acquisition and processing techniques and then details of each of the turbines and study sites. In order to assess whether each of the turbines would generate frequencies in the 4–5 Hz band, critical for EKA, the spectral characteristics are analysed and the sources of key frequencies identified. Previous studies (Styles *et al.* 2005; Saccorotti *et al.* 2011) have found that wind speed can affect the amplitude of the signal from large wind turbines. Therefore this, along with the relationship between seismic amplitude on the tower and foundation, are investigated for small wind turbines.

PREVIOUS STUDIES

Very few studies on the microseismic vibrations from wind farms have been carried out in either the UK or abroad. The first work was in the early 1990s by Legerton *et al.* (1996) at St Breock Downs in Cornwall, UK, a wind farm consisting of eleven Bonus 450 kW turbines. The study found that harmonic components of a prominent 0.5 Hz peak in the spectra were transmitted through the ground with particular peaks occurring at 0.5 Hz, 3 Hz, 4.5 Hz, 6 Hz and 7.5 Hz, as well as higher frequencies. The amplitudes of these frequencies were found to differ with wind speed, with different frequencies being more dependent on different wind speeds.

This was followed by work in the USA by Schofield (2002) to determine whether the seismic signals from the proposed large (300 turbines) Maiden wind project would be detrimental to the Laser Interferometric Gravitational Wave Observatory (LIGO) on the Hanford Reservation. The study focused on measurements of the vibrations from the Stateline Wind Project in Oregon, which consisted of 399 Vestas V47, 660 kW wind turbines and found results consistent with Legerton *et al.* (1996). Schofield (2002) identified peaks which increased in frequency as the rota-



FIGURE 1

Locations of each of the wind turbine sites, the Eskdalemuir array (EKA) and 50 km consultation zone.

tional rate of the turbines increased, before stabilising at high wind velocities when the turbines run at a nearly constant rotational rate. Similarly to the previous work, prominent frequencies were identified as harmonic components of the blade passing frequency of 0.49 Hz.

In 2004, work was carried out to investigate the nature and levels of vibration from wind turbines and whether these would interfere with EKA. The study (Styles *et al.* 2005; England, 2007) focused on twenty-six Vestas V47 660 kW turbines, the same model of turbine as studied by Schofield (2002), and situated on similar geology and topography to Eskdalemuir (Silurian Shales). Ten seismometers were deployed at locations up to 17 km away from the wind farm for a period of four months. The study found that the spectral content of the signal contained prominent frequencies in the 4–5 Hz band, critical to EKA.

Each of the above studies consisted of a shut-down phase where it was consistently found that the amplitude of the frequency spectrum from measurements recorded on the turbine clearly dropped, but the resonant frequencies were still visible, although at a much lower amplitude.

Fiori *et al.* (2009) carried out work in 2005 at the Schliekum wind farm near the Gravitational Wave Observatory (GEO600), located 25 km south of Hannover, with the aim of generating a model to predict the effect of a wind farm planned for construction close to the Virgo gravitational wave detector near Pisa, Italy. Their results show that the general amplitude of the spec-

trum increases with wind speed and that even when the turbine is not operational, some peaks are still visible, agreeing with the findings of Legerton *et al.* (1996) and England (2007). The proposed farm was installed by mid-2008 and plans had been submitted for an additional three 2 MW turbines. In 2009, Saccorotti *et al.* (2011) conducted measurements at Virgo to determine the nature and attenuation of the seismic signals from the existing wind farm and found results consistent with previous studies.

These studies have all shown that large wind turbines generate low frequency vibrations which are propagated many kilometres through the ground. However, the frequencies that are generated are not consistent through all turbine types. What makes this case study relevant is that no previous studies considered vibrations from small wind turbines.

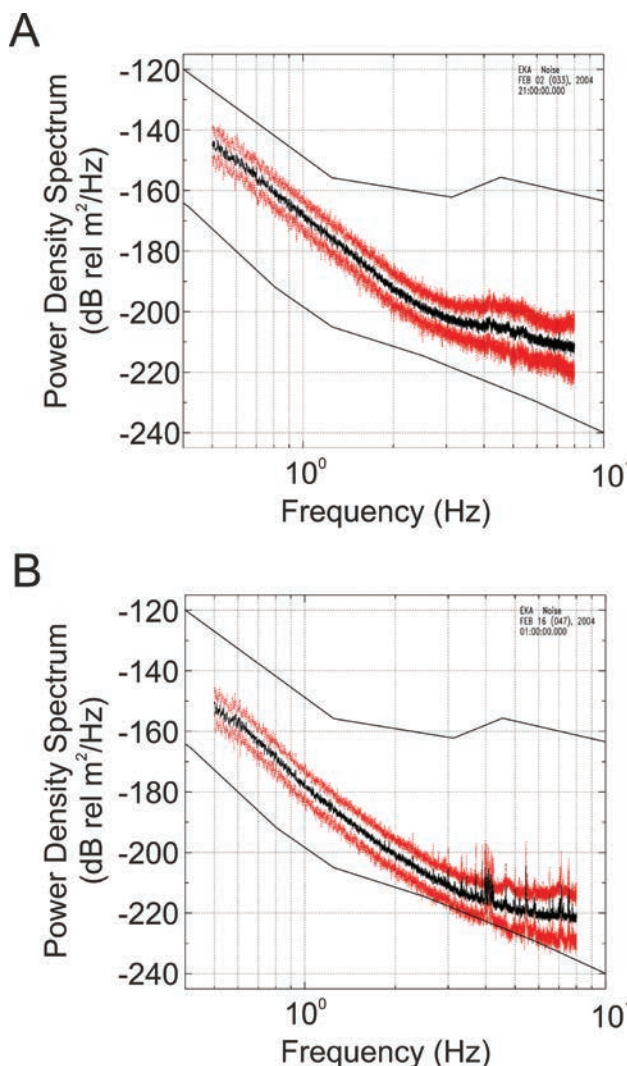


FIGURE 2
Power spectra from EKA at 12.86 m/s wind speed (A) and 0 m/s wind speed (B). The red lines are \pm two standard deviations from the mean (central black line). The outer black solid lines indicate the high and low noise models of Peterson (1993). After Bowers (2004).

ESKDALEMUIR SITE DESCRIPTION

Operational since May 1962 and situated between Moffat and Hawick in the Scottish Southern Uplands, EKA is an integral component of the IMS, an element of the verification regime for the CTBT. The UK is bound by the terms of the treaty to ensure the detection capabilities of the station are not compromised. The length of operation and geometry of the array (twenty broadband seismometers arranged in two almost perpendicular arms over 10 km with ten seismometers in each (Truscott 1964)) means that EKA is the longest serving steerable seismic array in the world. The array has the ability to record not just local signals (e.g. road traffic, wind, oceans, wind farms) but also signals which originate several thousands of kilometres away, including explosions and earthquakes. Over 400 signals associated with nuclear explosions have been recorded at EKA. The site is one of the seismically quietest in the UK and it has been shown by Elliot *et al.* (2004) that at windy times the seismic noise, above 2 Hz, is only 20 dB above the Peterson (1993) low-noise model and at quiet times less than 10 dB above the low-noise model (Fig. 2).

The work by Styles *et al.* (2005) showed that the vibrations generated by large wind turbines have a spectral content containing prominent frequencies in the 4–5 Hz band, a frequency band which is seismically very quiet at EKA and critical to the stations detection capabilities, lying in the centre of its 0.5–8 Hz pass band of interest (Bowers 2004; Styles *et al.* 2005). The frequency band is also seen to be generated by similar power turbines in experiments by Legerton *et al.* (1996) and Schofield (2002). As a consequence of the work, a 50 km radius consultation zone centred on EKA was implemented by the UK Ministry of Defence for all new wind turbine developments. A model was derived to calculate the aggregate vibrational contribution from any planned wind farm in the vicinity of EKA. A threshold value was obtained using the median value of 330 half hour data sets of seismic background noise levels at wind speeds greater than 12.8 m/s recorded on the array. A maximum permissible aggregate background noise budget of 0.336 nm was introduced to allow wind turbine developments in the zone to a level that would not interfere with the detection capabilities of the station. This is the model currently in use by the UK Ministry of Defence to assess whether an objection should be raised for planning applications within the consultation zone. No distinctions are made between different types of wind turbines based on rated power output or hub height.

Since the time of the Styles study, wind farm development in the area has increased and the noise budget is close to capacity. This has led to a total ban by the UK Ministry of Defence on all new developments within the zone, including small (≤ 50 kW) wind turbines.

There are over ten manufacturers of small wind turbines in the UK and more abroad. In recent years, demand for small and medium (50–500 kW) wind turbines has increased considerably, with RenewableUK reporting that deployed capacity in the UK reached over 100 MW at the end of 2012, an increase of 71% on

TABLE 1

Specifications of each of the wind turbines.

Manufacturer and Model	Power (kW)	Tower height (m)	Rotor diameter (m)
MEL - Gaia-Wind 133 (lattice tower)	11	18	13
WIG - Gaia-Wind 133 (tubular tower)	11	18	13
KIL - Proven 35-2	12.1	15	8.5
HAY - Endurance E-3120	50	24	19.2

the previous year. Therefore, this paper is important for assessing the impact that the increasing numbers of small wind turbine installations may have on sensitive scientific installations not only in the UK, but around the World and will use the Eskdalemuir seismological station as a case study.

DATA ACQUISITION AND PROCESSING

A combination of sensors was deployed at each site, selected from the following instrument pool:

- 1x Guralp CMG-6TD three-component broadband seismometer;
- 1x Guralp CMG-5TD three-component accelerometer;
- 6x Guralp CMG-5U single-component accelerometers;
- 1x Guralp CMG-DM24S6EAM six channel digitiser;
- 1x anemometer on a 4 m mast.

The instrument selection depended upon the site layout, equipment availability and the combination that provided the best resolution for both directional and attenuation measurements over a wide frequency band and distancing range. All sensors were set to the same sampling rate of 200 Hz on each channel and recordings were carried out over a seven day period. The sensors were deployed in the same way at each site.

The CMG-6TD was deployed, in line with Seis-UK's recommended field deployment guidelines (Brisbourne *et al.* 2013), in a hole 80–100 cm deep and 30 cm in diameter. A layer of clean sand approximately 2 cm deep is placed at the bottom and gently firmed down in order to provide a platform in which to level the sensor and hold it in place. To protect it from very wet conditions, the sensor was placed in plastic bags and sealed. The sensor is levelled by firmly pushing downward, and aligned North-South before the pit is backfilled with sand and tamped a little at a time to the top of the sensor. The CMG-5TD was deployed in the same manner.

Two CMG-5U accelerometers were attached horizontally and perpendicularly on the tower, using magnets. A third accelerometer was attached horizontally to the foundation of the turbine. At three of the sites (WIG, MEL and HAY), further accelerometers were buried in the ground, in pits approximately 30–50 cm deep and lined with builders' sand, in a similar manner to the CMG-6TD and placed in a radial line at 10 m, 20 m and 30 m from the wind turbine. These, combined with the sensor on the foundation, measured the radial component.

DATA PROCESSING

The anemometer was attached to a 4 m high mast. As this was not representative of the turbine height, the wind speed was corrected

to represent an estimate of the wind speed at hub height using equation (1) for wind shear, taken from Manwell *et al.* (2009).

$$v = v_0 \left(\frac{\ln(h/z)}{\ln(h_0/z)} \right), \quad (1)$$

where v_0 is the measured wind speed at height h_0 , v is the predicted wind speed at height h and z is the surface roughness length. There is an element of error to this calculation as z may change depending upon wind direction and site conditions.

Prior to processing, all seismic data was converted to acceleration, using the calibration data provided by Guralp and differentiated, if appropriate. The data was processed in the same manner for each turbine using a three-step method:

1. The data was split into 10 minute blocks, correlating to the wind speed reading times;
2. An acceleration power spectral density (PSD) function was calculated for each block using the Welch (1967) method:
 - a. Split the samples into M overlapping segments, each with length L and D samples apart, such that $(M-1)D + L = N$.
 - b. Each of the M samples is windowed using data windows $W(\xi)$, for $\xi = 0 \dots L-1$ and the Finite Fourier Transform performed on the sequences $X_1(\xi)W(\xi) \dots X_M(\xi)W(\xi)$ to obtain $B_1(n) \dots B_M(n)$. The M periodograms are obtained using,

$$B_m(n) = \frac{1}{L} \sum_{\xi=0}^{L-1} X_m(\xi) W(\xi) e^{-\frac{2\pi i \xi n}{L}},$$

where $m = 1 \dots M$ and $n = 0 \dots L/2$.

- c. The spectrum is an average of the periodograms,

$$\hat{I}_k \left(\frac{N}{L} \right) = \frac{1}{M} \sum_{m=0}^M \frac{L}{U} |B_m(n)|^2,$$

where,

$$U = \frac{1}{L} \sum_{\xi=0}^{L-1} W^2(\xi).$$

The result is an array of power plots (dB) vs frequency (Hz).

3. Displacement spectral plots were generated by integration using equation (2).

$$S_d(f) = \frac{S_a(f) / 4\pi^2 f^2}{4\pi^2 f^2} = \frac{S_a(f)}{16\pi^4 f^4}, \quad (2)$$

where $S_d(f)$ is the desired displacement PSD, $S_a(f)$ is the acceleration PSD and f is the frequency.

An interquartile mean was used to calculate an average PSD over a range of wind speeds, in order to reduce the effects of outliers on the calculated average.

THE WIND TURBINES AND STUDY SITE LOCATIONS

Four small wind turbines (Table 1) were chosen to represent the overall variation in design, power and operation of small wind turbines.

Gaia-Wind 133 (Tubular tower): Wigton, Cumbria, England (WIG)

The Gaia-Wind 133 11 kW wind turbine was developed in Denmark in the early 1990s, with the first turbine going operational in 1993. Unlike most wind turbines, the Gaia-Wind only has two blades, which rotate at a fixed speed of 56 rpm and are attached to a unique teeter hub. The turbine has a rotor diameter of 13 m and generates power at wind speeds between 3.5 m/s and 25 m/s. The turbine is available at two heights of 18 m or 27 m

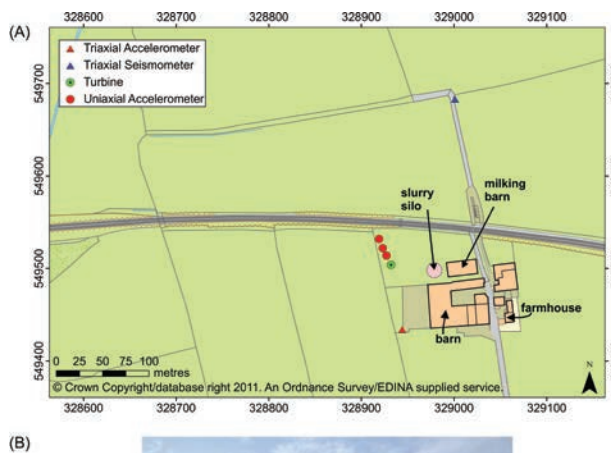


FIGURE 3

The Gaia-Wind 133 Tubular wind turbine test site details. A) The site at Wigton, Cumbria, in England. The map shows the location of the sensors in relation to the wind turbine and nearby buildings. B) The Gaia-Wind 133 tubular tower wind turbine.

on a tubular monopole tower. The former was monitored for this study. The turbine sits on a foundation of reinforced concrete, set in soil, with dimensions of 5 m x 5 m x 0.5 m.

There is an anemometer connected to the upwind side of the nacelle, which is used for monitoring the wind speed at hub height and controlling the operation of the turbine but the values are not logged.

This turbine is situated on private land at a farm just outside the village of Wigton in Cumbria, 13 km south-west of Carlisle and outside the Eskdalemuir exclusion zone. The turbine powers a dairy farm and is located in a field to the rear of the property. It lies north-west of the main farm building and approximately 40 m from the Carlisle to Barrow-on-Furness rail line (Fig. 3).

Gaia-Wind 133 (Lattice tower): Melrose, Scottish Borders, Scotland (MEL)

The Gaia-Wind 133 (lattice tower) wind turbine (Fig. 4) has the same foundation, power, rotation speed, blades and hub as the tubular tower Gaia-Wind 133. The main difference between the two is the tower design and height. The lattice tower is avail-

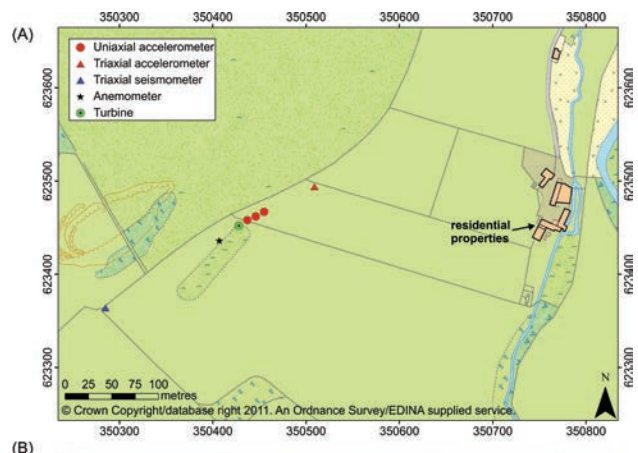


FIGURE 4

The Gaia-Wind 133 Lattice wind turbine test site details. A) The site at Melrose in the Scottish Borders. The map shows the location of the sensors in relation to the wind turbine and nearby buildings. B) The Gaia-Wind 133 lattice tower wind turbine.

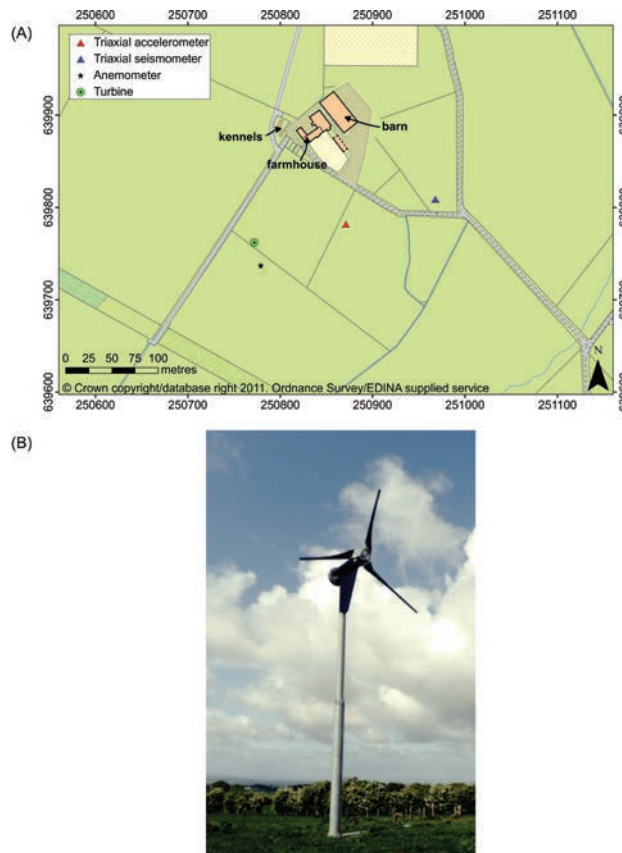


FIGURE 5

The Proven 35-2 wind turbine test site details. A) The site at Kilmarnock, Ayrshire in Scotland. The map shows the location of the sensors in relation to the wind turbine and nearby buildings. B) The Proven 35-2 wind turbine.

ble in two heights of 15 m and 18 m, with the latter monitored for this study. This turbine is situated on private property, inside the Eskdalemuir consultation zone near Melrose in the Scottish Borders, 6 km south-east of Selkirk. It is on the top of a hill away from any buildings, more than a kilometre away from the nearest minor road and over 3 km from the nearest main road, the A7.

Proven 35-2: Kilmarnock, Ayrshire, Scotland (KIL)

The Proven 35-2 12 kW wind turbine is a three-blade machine and at the time of monitoring was the most popular of the three turbines sold by Proven. Unlike the Gaia-Wind 133 and the Endurance E-3120, the Proven turbine is self-regulating. The blades pitch and cone to regulate the speed. It has a rotor diameter of 8.5 m and operates at wind speeds between 3.5 m/s and 54 m/s. The direction in which the blades face is controlled by a rudder made from a glass thermoplastic composite which fits over the hub and round the top section of the tower. The turbine sits on a foundation of reinforced concrete, in soil, with dimensions of 3.7 m x 3.7 m x 1.2 m.

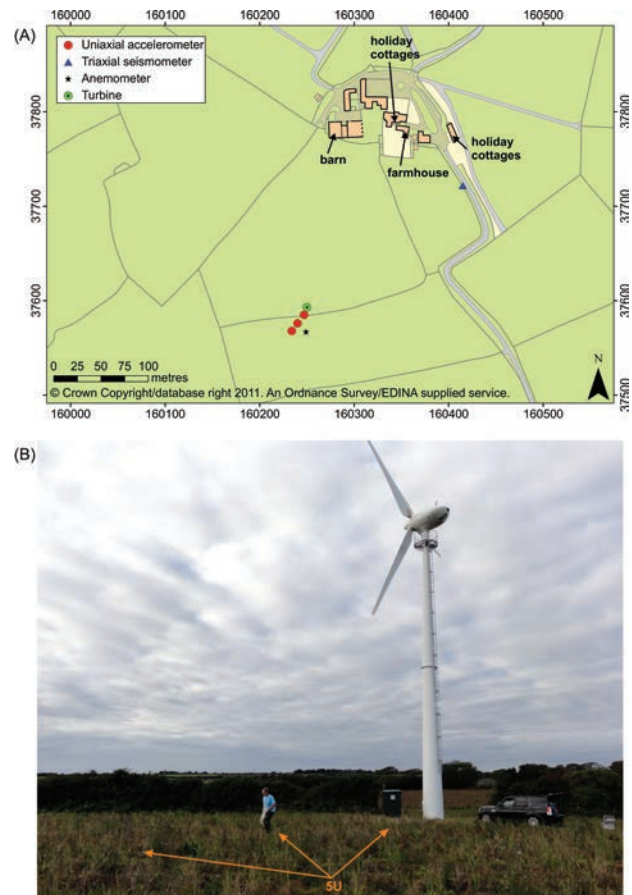


FIGURE 6

The Endurance E-3120 wind turbine test site details. A) The site at Hayle, Cornwall in England. The map shows the location of the sensors in relation to the wind turbine and nearby buildings. B) The Endurance E-3120 wind turbine with the location of the CMG-5U uniaxial sensors highlighted.

This turbine is located on farmland approximately 9 km east of Kilmarnock in East Ayrshire, Scotland. The site is 2.8 km north of the main A71 road and 1.5 km east of the A719. The wind turbine is used to power a farm and is located approximately 200 m south of the main farm buildings (Fig. 5).

Endurance E-3120: Hayle, Cornwall, England (HAY)

This is a three-blade small wind turbine with a rated power of 50 kW, at the upper limit of the definition of a small wind turbine. As with the Gaia-Wind 133, the E-3120 has a fixed rotational speed, operating at 43 rpm and a rotor diameter of 19 m. There is an anemometer connected to the upwind side of the nacelle. This is used by the on-board computer system to control the operation of the turbine. The turbine is available on a monopole tower at a height of either 24 m or 36.5 m. The former was monitored for this study. The turbine sits on a foundation of reinforced concrete, in soil, with a dimension of 6 m x 6 m x 1 m.

Lanyon Farm and holiday cottages are located 4 km east of

Hayle in Cornwall. The nearest main road, the A30 is 1.7 km away. The wind turbine is located in a field belonging to the farm and is used to power the farm and cottages (Fig. 6).

SEISMIC NOISE IN THE PROXIMITY OF SMALL WIND TURBINES

Spectral Characteristics

Each of the wind turbines exhibit different spectral characteristics, although the amplitude on the tower is similar (Fig. 7). In general, the average amplitude decreases with distance, indicating that the signal predominantly originates from the turbine, due to the siting and orientation of the sensors. The exception to this is WIG, which is a seismically noisier site and has a higher background noise level on the sensor at 190 m compared to the other three sites. Additionally, there are also fewer obvious peaks in the spectra for the sensors in the ground furthest away, at all sites.

KIL and MEL both exhibit few peaks in the spectra from the sensors placed in the ground between 10 and 100 m. This data was collected on strong motion accelerometers with a higher noise floor than the seismometer. The flat line spectra visible for these sensors indicates that there is weak ground motion and any signal originating from the turbine has an amplitude too small to be detected on such a sensor. These two turbines additionally display little amplitude above the seismometer noise floor at 190/200 m, indicating that the majority of the energy has attenuated by this distance. The other two turbines contain some minor detail in the spectra at all distances. The lack of amplitude may be due to local site conditions, for example soil properties which may present higher attenuation at one site compared to another; or turbine structure, for example the lattice tower may not, given the different lengths of the struts, transfer as much energy as an equivalent height tubular tower.

KIL is the only turbine of the four to have a variable rather than fixed rotor speed. It is a self-regulating turbine with a higher rotor speed at higher wind speeds. This affects the blade passing frequencies, which cause any peaks in the spectra related to the blade passing to shift depending upon the rotor speed.

The spectra for the HAY sensors in the ground at 10, 20 and 30 metres show spurious peaks every 1 Hz. This is thought to be caused by an electrical grounding issue with the digitiser. Taking this into account, the sensors in the ground at each of the sites show few spectral peaks below 4 Hz.

The blade rotation harmonics at multiples of 0.93 Hz for WIG and MEL and multiples of 0.72 Hz for HAY are significant in the spectra below 12 Hz, from the data on the tower and at the base (KIL is a variable speed turbine, so has no fixed blade rotation frequency). Below 12 Hz, there are two peaks visible on the tower spectra for MEL at, 2.5 Hz and 3.5 Hz, which cannot be attributed to blade rotation harmonics. These are not visible in the ground, but are still present on the foundation. These two peaks are likely related to the resonant modes or mechanical mechanism of the turbine.

Signal Identification

All of the turbines are defined, by the manufacturers, to have a cut-in wind speed of 3.5 m/s, therefore the wind speed was grouped into less than 2 m/s to ensure the wind turbine would not be generating and greater than 3.5 m/s for when it is turning. Signals were attributed to the turbine if they were larger on both the tower and foundation than in the ground.

Westwood (2012) describes a multiphysics computational model of a Gaia-Wind 133 tubular tower turbine and calculation of the resonant modes. Using these results it is possible to identify the origin of the frequencies in the on-tower spectrum for

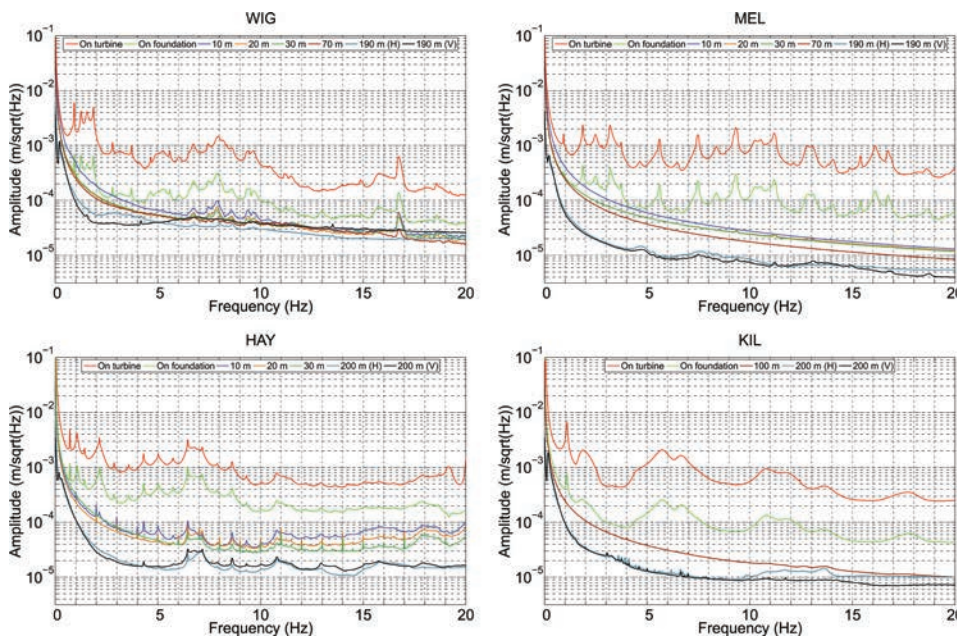


FIGURE 7

Displacement frequency spectra for sensors at a range of distances from each of the four wind turbines, recorded when the turbine was in operation and the wind speed above 3.5 m/s.

WIG (Fig. 8). Two types of peaks were identified: peaks associated with the resonant modes of the turbine and those which were linked to the blade rotation rate. Each resonant mode has two frequencies relating to the side-side (swaying) and fore-aft (rocking) motions. The 1st and 2nd resonant modes at 1.1 Hz, 1.9 Hz and 9.7 Hz are apparent at both ranges of wind speed. It is therefore possible that these frequencies could transfer into the ground at wind speeds less than 2 m/s, though at much lower

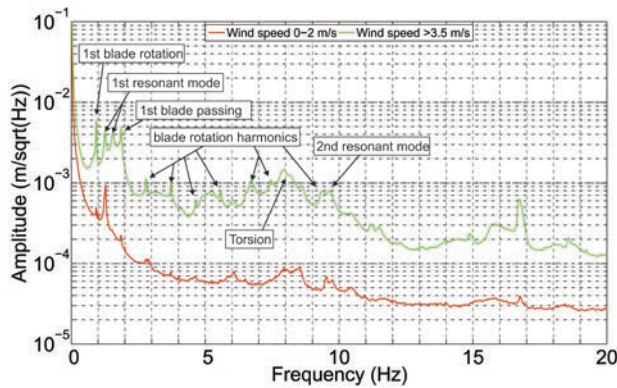


FIGURE 8
An annotated displacement frequency spectra using data recorded on the tower of the Gaia-Wind 133 tubular tower turbine at low (<2 m/s) and high (>3.5 m/s) wind speeds.

TABLE 2

Frequency peaks visible in the spectra for the three fixed speed turbines seen on the tower and the foundation. Top: the rotation frequency harmonics which decrease significantly in amplitude or are not discernible at low wind speeds. Bottom: The resonant modes of the structure which are significant through all wind speeds.

Comments	Approx. frequency at wind speeds >3.5m/s (Hz)	
	MEL and WIG	HAY
Rotation frequency	0.93	0.7
2 nd harmonic (blade passing - MEL and WIG)	1.85	1.4
3 rd harmonic (blade passing - HAY)	2.8	2.1
4 th harmonic	3.7	2.9
5 th harmonic	4.6	3.6
6 th harmonic	5.6	4.3
7 th harmonic	6.7	5
8 th harmonic	7.5	5.7
9 th harmonic	8.4	6.5
10 th harmonic	9.3	7
11 th harmonic	10.2	7.9
12 th harmonic	11.2	8.6
Other higher harmonics are also discernible		

Comments	Approx. frequency (Hz)		
	MEL	WIG	HAY
1 st resonant frequency (both variation identified for WIG)	2.5	1.2 and 1.5	1.1
2 nd resonant frequency (very close to the blade passing frequency for HAY)	3.2	9.6	2.1

amplitudes. For the other two fixed speed turbines (MEL and HAY) the two types of peaks were discriminated between by comparing the spectra at both of the above wind speed ranges and the calculation of the expected blade rotation rate. Table 2 summarises the key frequencies visible in the spectra and their sources for each of the fixed speed turbines.

The varying rotation rate of KIL leads to shifting frequency peaks within the spectra for the blade passing frequency. These peaks increase in frequency as the rotation rate (and wind speed) increase. This agrees with the findings observed by Schofield (2002) for larger variable speed wind turbines. The turbine operates a self-regulating blade bending which stabilises the frequency and amplitude. There are far fewer peaks visible in the spectra for this turbine than the other three (Fig. 7).

WIND SPEED AND AMPLITUDE

Spectra were calculated over 0.5 m/s wind speed intervals (Fig. 9) in order to observe frequency peaks visible throughout the full range of wind speeds. The spectra indicate a gradual increase in amplitude with wind speed both on the tower and foundation, up to a speed where the spectra each start to overlap each other. There is also a significant decrease in amplitude from the tower to foundation

A selection of peaks from Table 2 (highlighted in Fig. 9) was used to observe the relationship between seismic amplitude and wind speed (Fig. 10) using a linear regression calculation. To

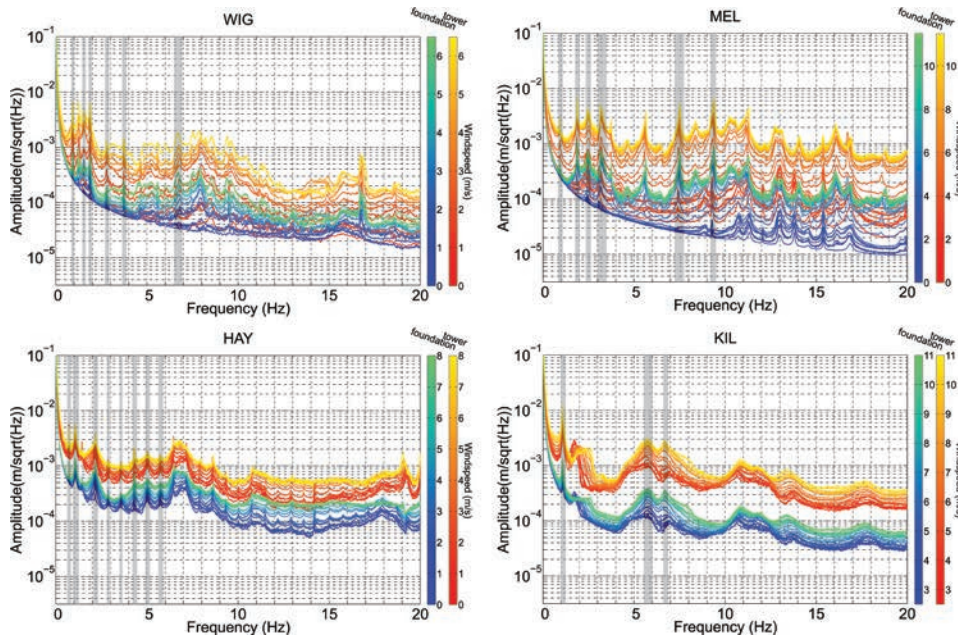


FIGURE 9

The spectra calculated over 0.5 m/s ranges from data recorded on the tower (red to orange) and on the foundation (blue to green). The highlighted frequencies are those used for the wind speed analysis.

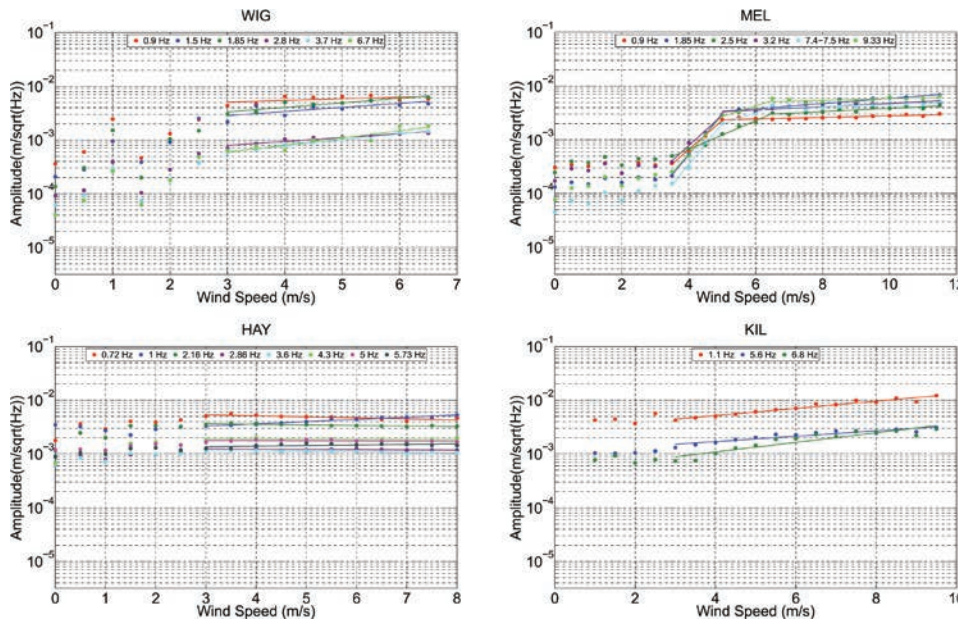


FIGURE 10

The relationship between displacement seismic amplitude recorded on the tower and wind speed for each of the four turbines.

ensure that the turbine was operational, only wind speeds greater than 2.5 m/s were included. Both WIG and HAY show two distinct groups of frequencies. The lower amplitude group contains frequencies which are harmonics of the higher amplitude group. Both turbines have a resonant mode frequency in the higher amplitude group. For HAY, this frequency displays a slightly different gradient, compared to the blade rotation harmonics which are almost constant, whereas for WIG it is the intercept which is distinctly different.

MEL presents a more complicated relationship between wind speed and amplitude, which is most likely due to the lattice struc-

ture resonating differently to the tubular towers. The 1st blade rotation and blade passing frequencies show a relationship with a change of gradient occurring at 5 m/s. The two frequencies which are not associated with the blades also contain a change in gradient, although for 2.5 Hz, this occurs at a different wind speed. The blade rotation harmonics at 7.5 Hz and 9.3 Hz (8th and 10th harmonics respectively) present two changes in gradient; one at 5 m/s and the second at 6.5 m/s. These match with the wind speeds of the gradient changes for the other frequencies. These relationships are summarised in Table 3 which shows the significant differences between the tubular tower turbines and the lattice.

TABLE 3

The equations for calculating seismic amplitude on the tower, with respect to wind speed (w), at HAY, WIG and MEL, for a range of frequencies. The blue rows indicate the fundamental blade rotational and blade passing frequencies, the pink rows are harmonics of these and the green rows, structural resonant frequencies, not related to the blade rotation frequencies.

HAY	
Frequency (Hz)	Seismic amplitude on the tower
$w > 2.5$	
0.72	$0.005e^{-0.2w}$
1	$0.0025e^{-0.09w}$
2.16	$0.004e^{-0.01w}$
2.86	$0.001e^{-0.01w}$
3.6	$0.001e^{-0.1w}$
4.3	$0.002e^{0.1w}$
5	$0.002e^{0.1w}$
5.73	$0.001e^{0.03w}$

WIG	
Frequency (Hz)	Seismic amplitude on the tower
$w > 2.5$	
0.9	$0.041e^{0.07w}$
1.5	$0.017e^{0.18w}$
1.85	$0.018e^{0.19w}$
2.8	$0.0005e^{0.17w}$
3.7	$0.0003e^{0.25w}$
6.7	$0.0002e^{0.31w}$

MEL					
Frequency (Hz)	Seismic amplitude on the tower				
	$3.5 < w < 6.5$	$3.5 < w < 5$	$5 < w < 6.5$	$w > 5$	$w > 6.5$
0.9		$4.5 \times 10^{-6}e^{1.3w}$		$2 \times 10^{-3}e^{0.03w}$	
1.85		$0.5 \times 10^{-6}e^{1.8w}$		$2 \times 10^{-3}e^{0.1w}$	
2.5	$57 \times 10^{-6}e^{0.6w}$				$2 \times 10^{-3}e^{0.07w}$
3.2		$4.2 \times 10^{-6}e^{1.3w}$		$2 \times 10^{-3}e^{0.1w}$	
7.4-7.5		$0.3 \times 10^{-6}e^{1.8w}$	$15 \times 10^{-3}e^{0.5w}$		$3 \times 10^{-3}e^{0.05w}$
9.33		$0.8 \times 10^{-6}e^{1.6w}$	$28 \times 10^{-3}e^{0.5w}$		$4 \times 10^{-3}e^{0.03w}$

This demonstrates that each small wind turbine generates different frequencies and amplitudes with respect to wind speed and that there is no single rule which applies to all small wind turbines. Additionally, the relationship between wind speed and amplitude for large wind turbines, as defined by Styles *et al.* (2005), Schofield (2002) and Saccorotti *et al.* (2011) does not appear to apply to small wind turbines.

Tower to Foundation Relationships

Using the same frequencies as for the wind speed analysis, the relationship between seismic amplitude (S_x) on the tower and on the foundation (S_y) can be obtained (Fig. 11). Each turbine demonstrates a strong positive relationship:

$$\begin{aligned}
 \text{WIG} \quad S_y &= 0.09S_x^{0.9} \\
 \text{MEL} \quad S_y &= 0.19S_x^{0.9} \\
 \text{HAY} \quad S_y &= 0.04S_x^{0.75} \\
 \text{KIL} \quad S_y &= 0.04S_x^{0.8}
 \end{aligned} \quad (3)$$

The coefficients of determination are 0.97 (WIG), 0.89 (MEL), 0.95 (HAY) and 0.998 (KIL). This indicates that the predicted amplitude on the foundation, using the amplitude from the tower, is a good fit to the observed data.

Tower to Ground and Foundation to Ground Relationships

A similar analysis was attempted for the relationship between the amplitude on the tower and in the ground at 190/200 m and also between the amplitude on the foundation and in the ground at 190/200 m. However, there are not enough discernible peaks in the spectra from the seismometer to perform a detailed and thorough analysis.

CONCLUSIONS

This study set out with the aim of determining whether small wind turbines generate vibrations at frequencies in the 4–5 Hz band which could be detrimental to the listening capabilities of EKA. The vibrations from four small wind turbines were measured using a combination of sensors attached to the tower and at distances of up to 200 m from the turbine.

The results demonstrate that vibrations from the turbines are transferred into the ground and propagate away from the turbine. However, the spectral content of the signal is specific to each turbine, although, each has noticeable peaks in the 4–5 Hz band which is critical for EKA. Identification of the source of specific frequencies to the blade rotation, its harmonics and to the resonant frequencies of the turbine showed that at low wind speeds the resonant frequencies can be observed on the tower and found

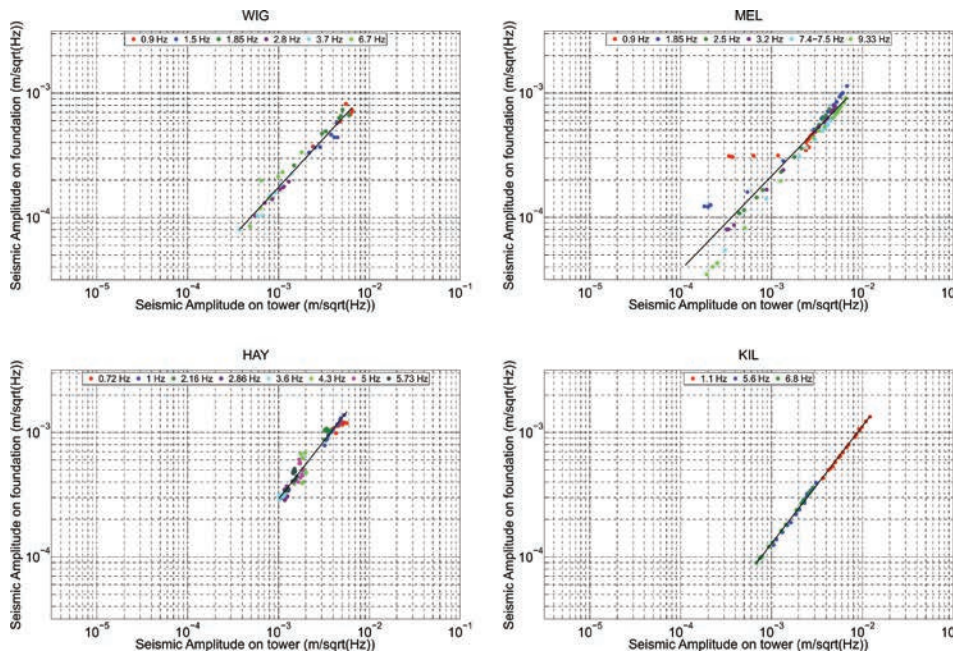


FIGURE 11

The relationship between displacement seismic amplitude recorded on the tower and the foundation.

dation. The decrease in amplitude from the tower to the foundation has been shown to fit a power relationship, which is different for each make of turbine. At 200m, the signals from the lower power, shorter turbines (MEL, WIG and KIL) are less discernible in the spectra. The height of the towers and different foundations are likely to affect the frequencies that are transferred into the ground. This, together with local site conditions, may affect the propagation and power of the signal; for example soil properties may present higher attenuation at one site compared to another.

The sensors in this study were all deployed in the near-field. Assuming that attenuation is higher in the near-field than the far-field, then from the results at 200 m it is likely that the amplitude will decrease quickly enough such that the far-field signal will be negligible.

An analysis of the relationship between wind speed and seismic amplitude on the turbine showed that the power-law defined for large turbines in previous studies does not hold for small turbines. The relationship between wind speed and amplitude is individual to each wind turbine and the frequency band of interest, although each fits an exponential relationship.

Based on the findings of this work, it is unlikely that one common vibration model, similar to that derived by Styles *et al.* (2005) for large wind turbines, can be derived for all small turbines and each type may well need to be treated on an individual basis.

One of the main limitations to this study is the location of the sensors, further studies carried out on small wind turbines could be used to assess the vibrations at greater distances and in the far-field. This study only used one anemometer to record wind speed. Recording wind speed data at two or more heights for any future studies would enable a more accurate calculation of the wind shear component. Additionally, advanced signal processing techniques, such as wavelet analysis, may provide further infor-

mation of the resonant modes of the turbines. Further studies of medium sized wind turbines (> 50kW and < 500kW) will allow a more complete picture of the vibrations from wind turbines to be observed in order to determine if a model similar to that derived by Styles *et al.* (2005) can be used to predict the amplitude of vibrations from turbines of all heights and power. In the meantime, based on the findings in this paper, small wind turbines in the vicinity of EKA could be considered on an individual basis, prior to planning being granted.

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